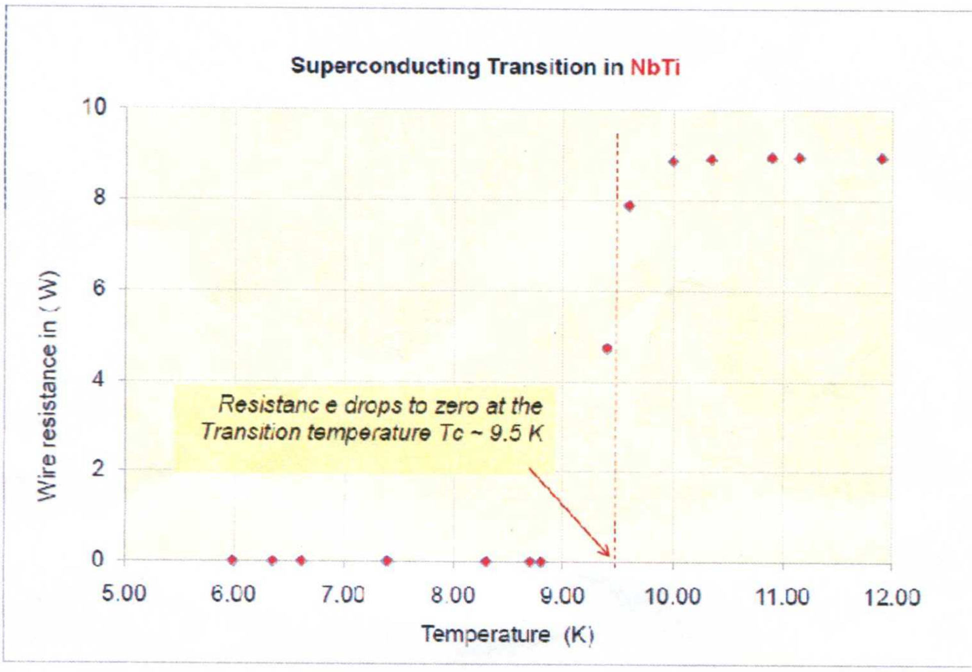
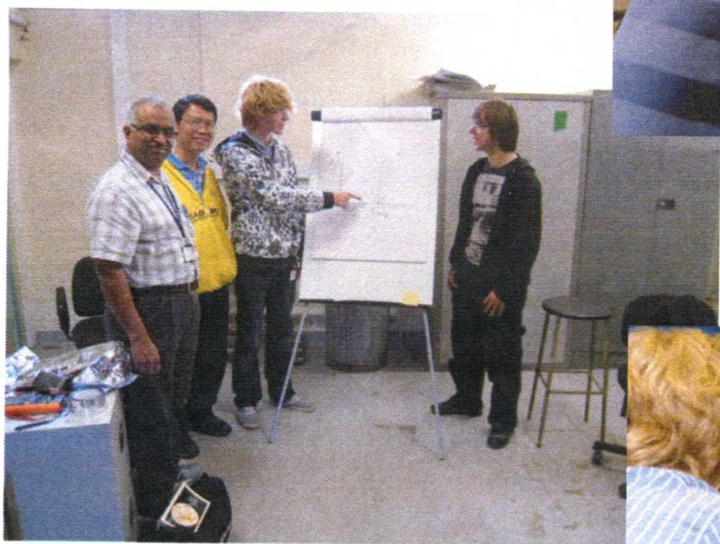
Nuffied Students demonstrate the phenomenon of Superconductivity

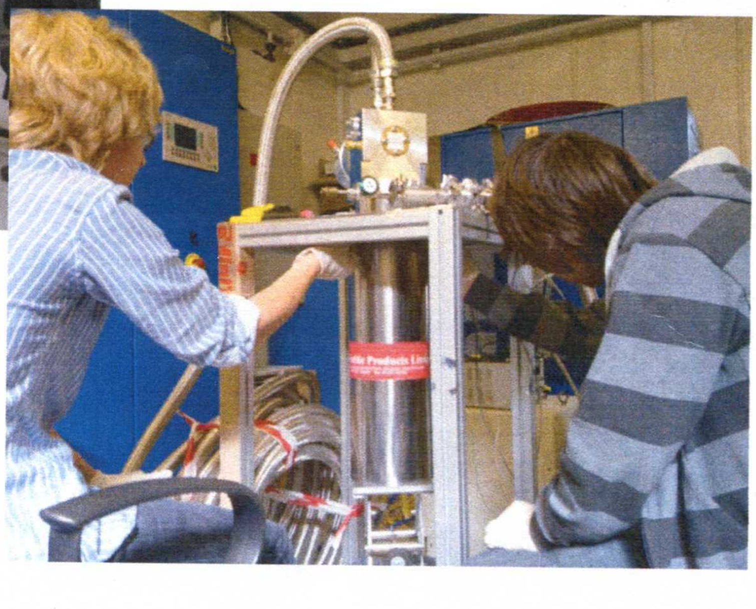
Adam McAteer and Keir Pearson, two summer students spent 4 weeks in August at the Cockcroft Institute to get an insight into conducting real life physics experiments. Their visit was supported by Nuffied foundation. Their primary assignment was to install and commission a pulse tube cryocooler for developing an experimental facility for the laboratory to conduct small experiments at low temperatures down to 4K (- 269 C). Adam and Keir not only were successful in establishing the facility but also added excitement to it by demonstrating the phenomenon of superconductivity by measuring the resistance of NbTi wire- filament through the superconducting transition.



Many thanks to Adam and Keir, their efforts have now provided a new experimental tool to the laboratory where small components can be characterised at low temperatures in just few days.

Kai Hock (CI) supervised this experiment while Shrikant Pattalwar (ASTeC) provided the overall guidance. Our best wishes to Adam and Keir for A level studies.





Demonstrating superconductive properties of metals at temperatures approaching 4 Kelvin.

By Keir Pearson
The King's School in Macclesfield, 2010
Working at:
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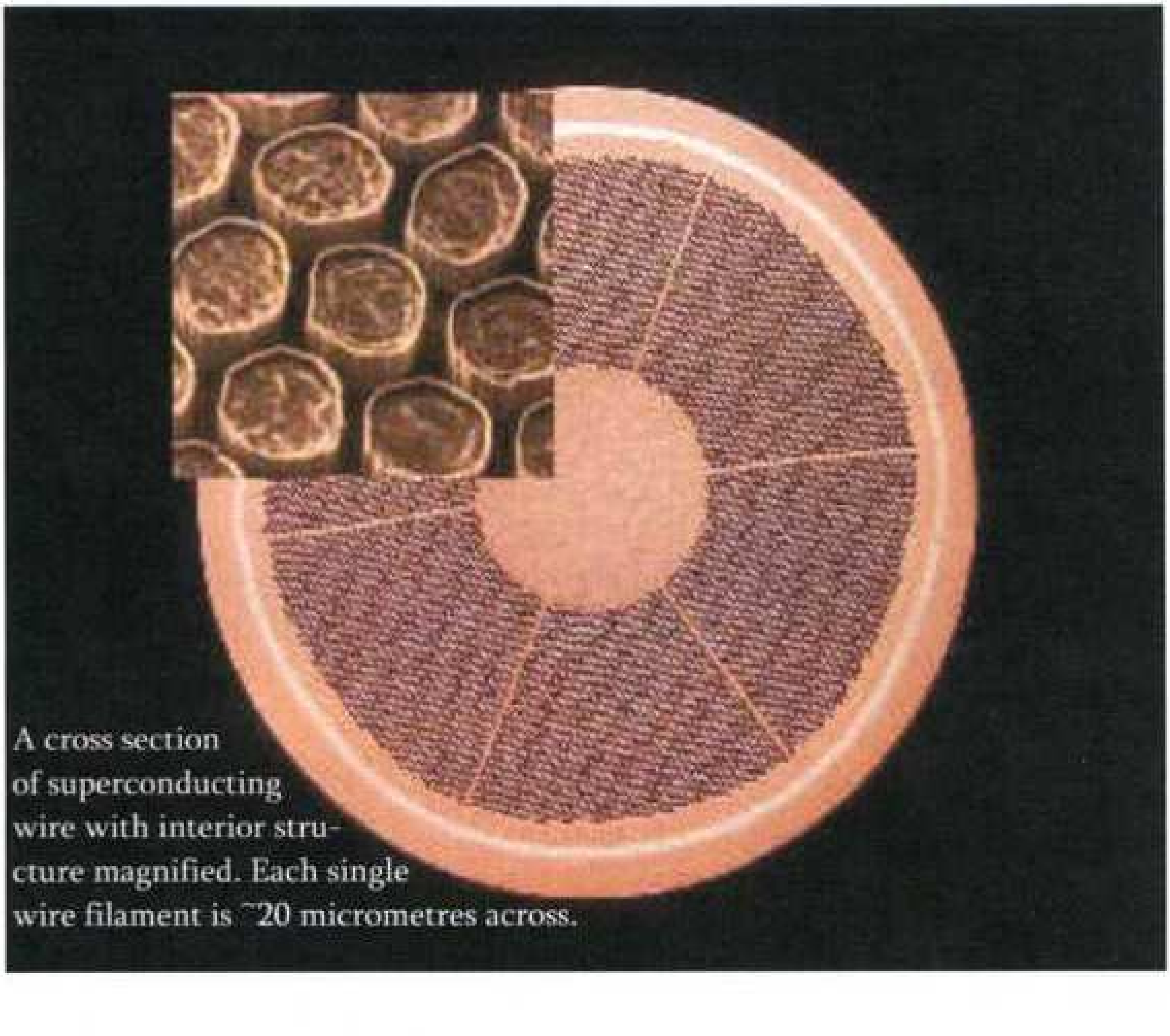


A cross section of superconducting wire with interior structure magnified. Each single wire filament is ~20 micrometres across.

CONTENTS

Abstract

Over the course of four weeks I, and another person on the Nuffield scheme set up a cryocooler and necessary attachments, and measured the temperature at which our sample of superconducting wire's resistance dropped to zero, therefore becoming superconductive (the critical temperature T_c). We found that the T_c of NbTi wire, which we used was ~ 9.5K We also measured the cooling power of the cryocooler, i.e the power of the heater needed to 'overpower' the cooler at its lowest temperature. The purpose of this project was not to break new ground scientifically, but rather give a window on the skills needed for work in the field of cryogenics, and in doing so the assembled cryocooler could be used for further experimentation.

Introduction

What is already known?

The phenomenon of superconductivity has been firmly on the scientific radar for just under a hundred years, since its discovery in 1911 by Heike Kamerlingh Onnes. He, in a similar experiment to the one carried out, used helium coolant, liquefied by a process of pressurisation and depressurisation, to cool his sample to 4.2K (K=Kelvin. 0K is absolute zero, -273°C, the point at which atoms stop moving. Essentially, the Kelvin scale is just the Celsius scale +273) and measured the voltage and current through the sample. He was surprised to discover that there was absolutely no electrical resistance in the sample at all! Since then superconductivity has been, and is still being, thoroughly investigated, with older, metal superconductors which work at temperatures approaching absolute zero being superceded by newer ceramic superconductors which are effective at temperatures ~125K and more recently ones of critical temperature ~254K, a record at time of writing and close to temperatures found in high quality freezers (though this claim is dubiously authentic). As you can see, superconductor technology is still a long way from perfection, i.e room tempera-

ture superconductors, but the dividends will be immense, an age of floating trains and superpowerful desktop computers, as well as much more efficiency in electrical circuitry. In particular, the metal Niobium has found common usage in superconductive sci-

Uses

Superconducting magnets are some of the most powerful electromagnets we know of and are used in MRI scanners, NMR machines, mass spectrometers and the powerful magnets used to direct beams of particles in particle accelerators.In the future it is possible that superconductors could be used to form a smart grid; a modernized more efficient version of the current national grid. They could also be used to lift and propel maglev trains (the technology required for this has been developed but is rare as maglev trains cannot run on traditional rails so a whole new infrastructure would need to be built and the strong magnetic fields can cause complications for passengers with devices such as pacemakers, making magnetic shielding essential. In addition, the superconductors would need to be constantly cooled-a room temperature superconductor would be much more practical). Other possible uses include; electric power transmission, transformers and in power storage devices.

How does it work?

The best theory of how superconductivity works is the BCS theory produced by Bardeen, Cooper and Schreiffer. This explains superconductivity in materials with critical temperatures below 30 K (superconductors with critical temperatures above this are known as high temperature superconductors and the reasons for their superconductivity is still unknown). The critical temperature of a material is the temperature at which the resistance of the material drops to zero. This occurs in materials with regularly structured lattices which allow electrons to be coupled in pairs called cooper pairings. Electrons will normally repel but in this case a phonon interaction (ripples in the lattice formed by interac-

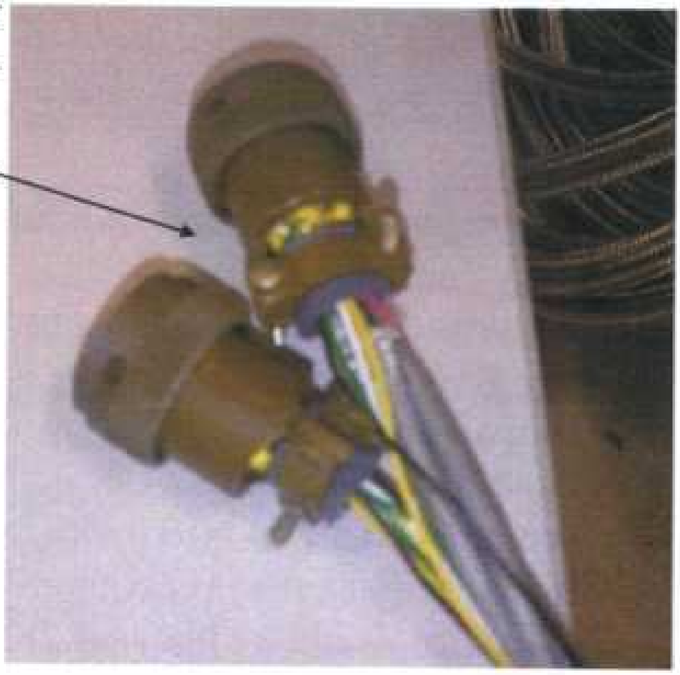
tions between the electrons and the protons in the nuclei) causes them to form a very weak bond. At normal temperatures the vibrations of the nuclei will break this bond but when the temperature is low enough the nuclei are vibrating so weakly that they cannot break these bonds. The bonds mean that even if one electron encounters some resistance the other can "pull" it along and when this is done by all the electrons in a material the resistance drops to 0.

What did we set out to find out, and what problems did we encounter?

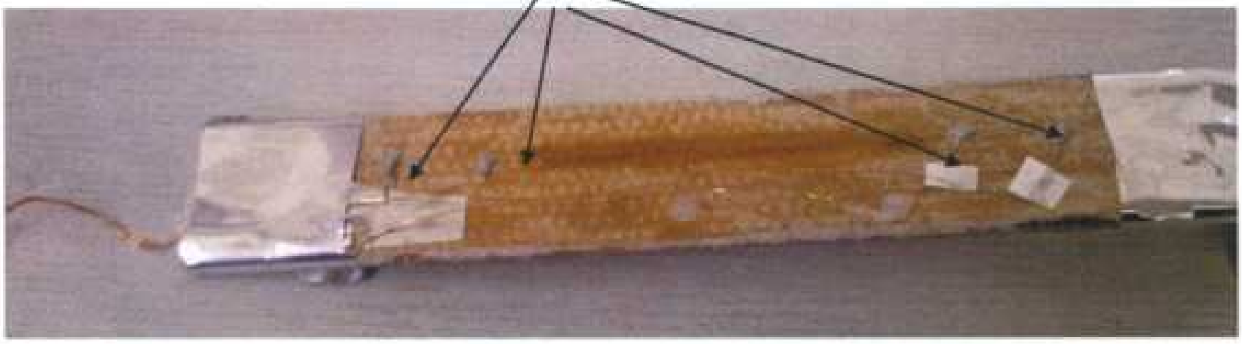
Our project was to set up a brand new cryocooler, fitting all necessary components to it so that it could measure the critical temperatures of various samples in future. This would hopefully not only give us experience of the manual skills needed in science, but also help teach us the principles of cryogenic physics. We also did some testing of our own, measuring the critical temperature of a sample of NbTi wire, and finding out the wattage cooling capacity of the cryocooler. We hypothesised that the T_c of the NbTi wire would be above 4.2K. Previous experimentation has achieved a T_c of ~10K. However, to do it, we had to overcome the problem of the low temperatures within the chamber's effect on our wiring. This we overcame by using uncoated, enamelled wires inside, so that gas could not be released by the plastic sleeves used on normal wires and ruin the vacuum, which in turn would cause the outside of the cooler to cool down rapidly, (heat would start being conducted and convected away from the outer shield) which is extremely dangerous, leading to cold burns as well as equipment failure.

Methodology

We were given an SRP-082B Pulse Tube cryocooler, mounted on a table with a hole cut through to allow access to the innards of the machine. This was covered by a radiation shield and an inner shield, so, in order to begin wiring, these had to be removed. After removal we consulted the diagram and wiring table we were given. There were two sets of wires, one for the inside of the cooler, and one for the outside. We began by wiring up two 25 pin plugs, one with 2 sets of 4 wires, another with one set, these would be plugged into the temperature indicators. A set of 4 loose plastic wires was also soldered on. The other ends of these wires (except the loose plastic ones) were soldered to a circular plug, which would act as an intermediary port between the interior and exterior wiring systems. The interior wiring was composed of unsleeved, enamelled twisted-pair copper wires held together by threads woven through, and thick single wires. These wires were then soldered to mounted pinboards, onto which the thermometers and heaters (in series) were then soldered. The wiring was then complete. The thick single copper wires were then found to be un enamelled, and so had to be removed to prevent short-circuiting, which would send confused signals to the temperature indicator. The necessary equipment to achieve vacuum and cooling were also attached. A He gas compressor was affixed via a supply and recovery tube, to provide the liquid helium needed to cool the cryochamber.. A water chiller was also added, to take the heat from the liquid helium coming in from the recov-

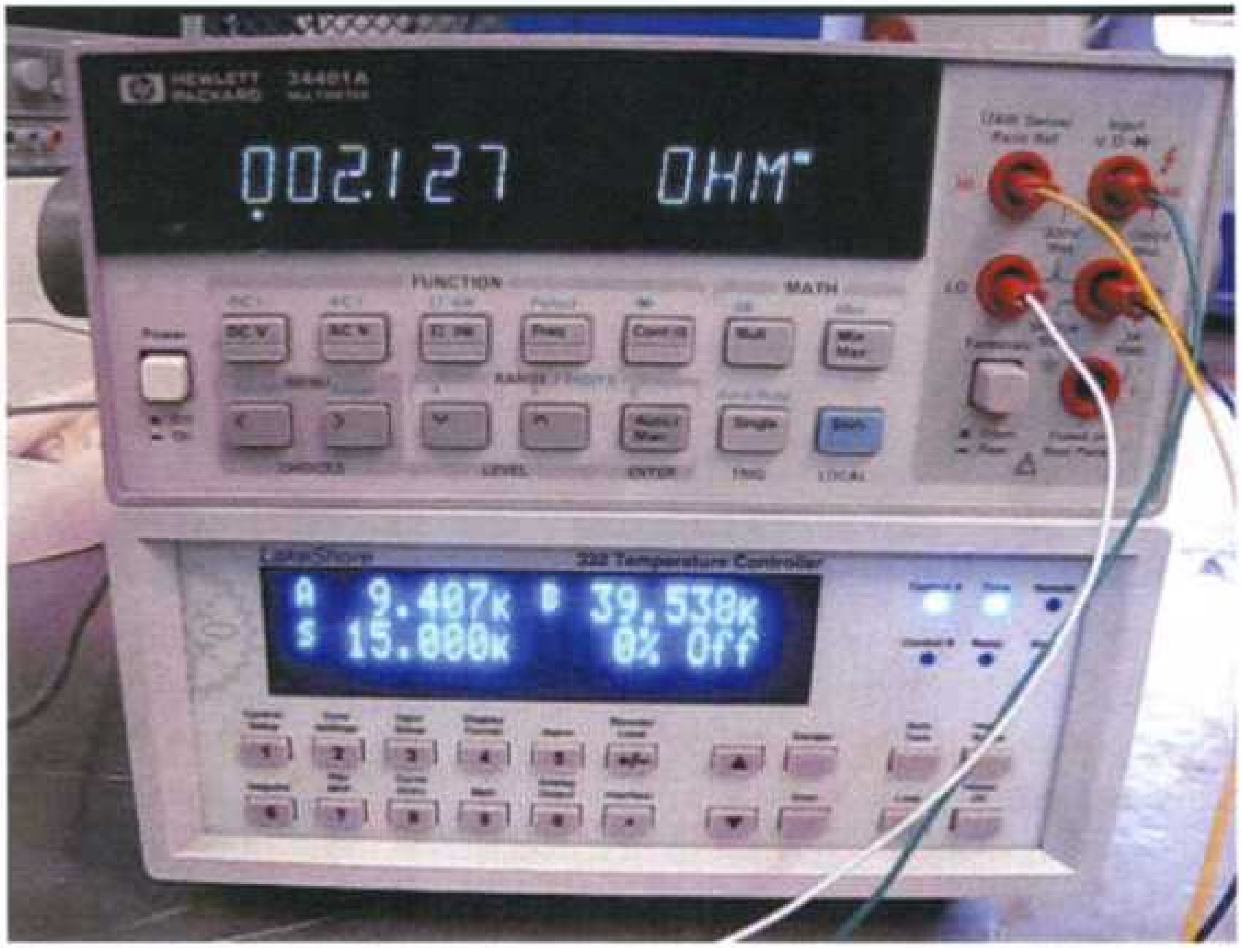


ery pipe. A turbomolecular pump was also affixed of sufficient power to achieve high vacuum. Between connections secured by clamps, 'O' rings were placed for maximum leak prevention. On first trial run the machine was stopped once it reached 200K, as water in chiller was becoming too hot. Inspection revealed an unidentified object. It was removed. We restarted the cooler the next day, and high vacuum was achieved. Once more water chiller failure prevented cooling past 4.7K. The superconducting wire sample holder was constructed (twice) and the wire itself was secured by aluminized mylar tape and GE/CMC varnish.



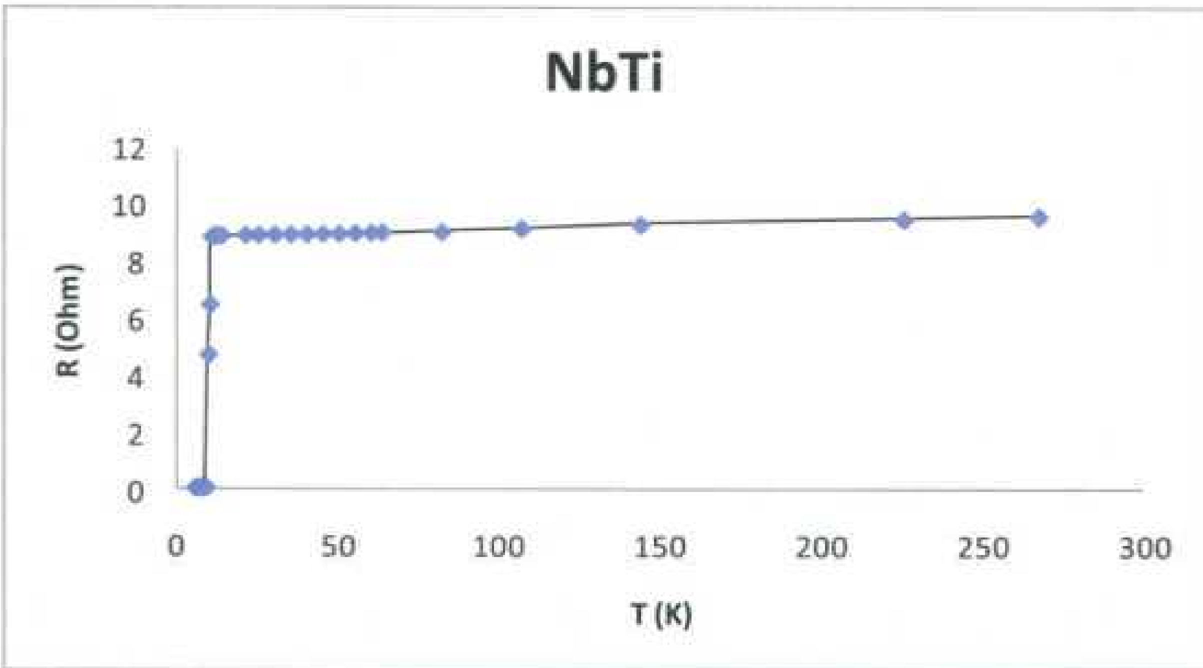
Copper wires were attached in [V+/I+]/ [V-/I–] pairs, secured at one end to the superconducting wire by silver epoxy and at the other end, soldered to a pinboard. A screw was placed in a copper tube and wire wrapped around it to act as a 'heat sink' to take out excess heat from the surrounding metals. The inner radiation shield was wrapped in aluminium superinsulation to prevent excess radiation to the inner contents.. The cooler was restarted, but the vacuum pump struggled to get past 7.3 mbar pressure. Eventually we attained high vacuum, and we began to cool the cryocooler.. We set up a multimeter to measure current and voltage, and a power supply, giving 30V. We measured current and voltage through the superconductor. At the point when voltage became 0, superconduction had been achieved, at a temperature of approximately nine degrees Kelvin. The next day we took more accurate measurements with a large multimeter measuring straight resistance, after replacing both the sample holder and the super insulation, having replaced that with aluminised mylar tape.

This time results were more systematically obtained by repeated cooling and warming of the cooler at temperatures above and below the transition temperature of the wire and taking constant measurements. This time the transition temperature was clearly seen to be around 9.5 K.



The above picture shows the measuring equipment when the sample was on the verge of becoming superconductive. The resistance readings were varying wildly, and we must allow an adjustment of at least ± 0.1K due to unavoidable inherent limitations in both equipment and setup.

As you can see from the data, the resistance started to decrease rapidly at about 10 Kelvin, reaching superconductivity at 8.7K, although we can safely assume that the wire was superconductive around 1 degree above this, due to the delay involved in manually collecting data, and the uncertain, and sudden nature of the transition itself, as well as the fact that the thermometer was not directly next to the sample holder.

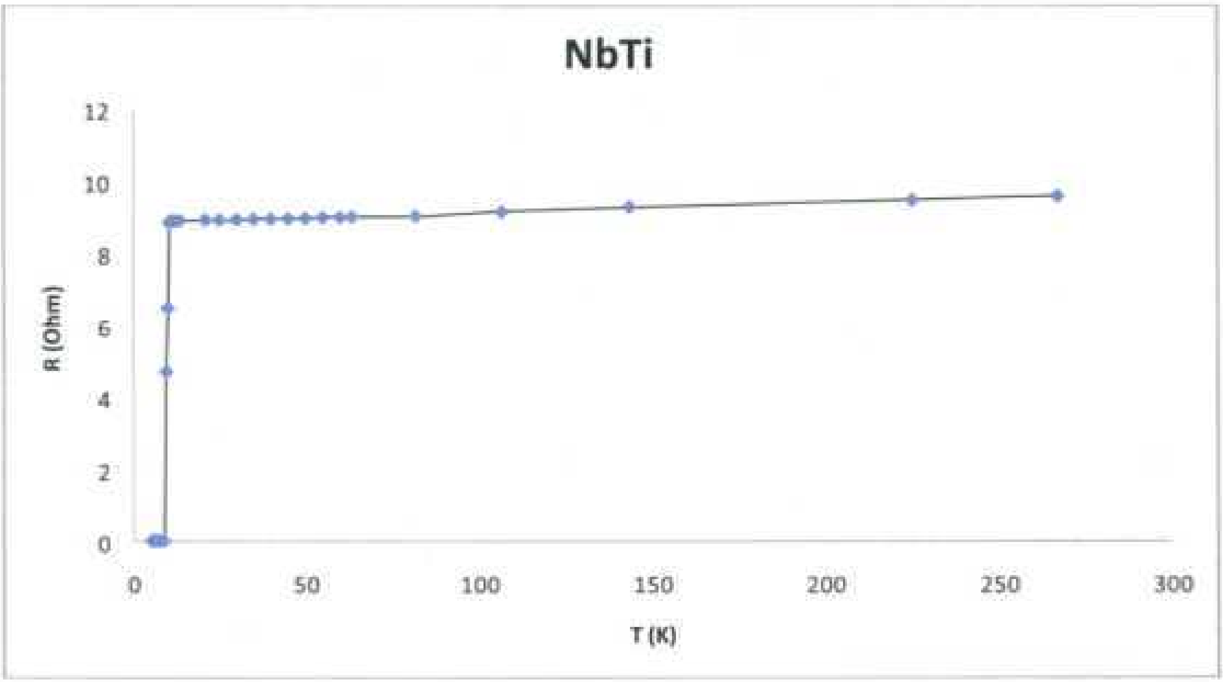


Cooling the sample from room temperature to approximately 3.7K again shows how sudden the transition to superconductivity is. Errors are extremely easy to make, especially as thermometer readings start varying a lot at extremely low temperatures, as do resistance readings when the sample is on the brink of superconductivity.

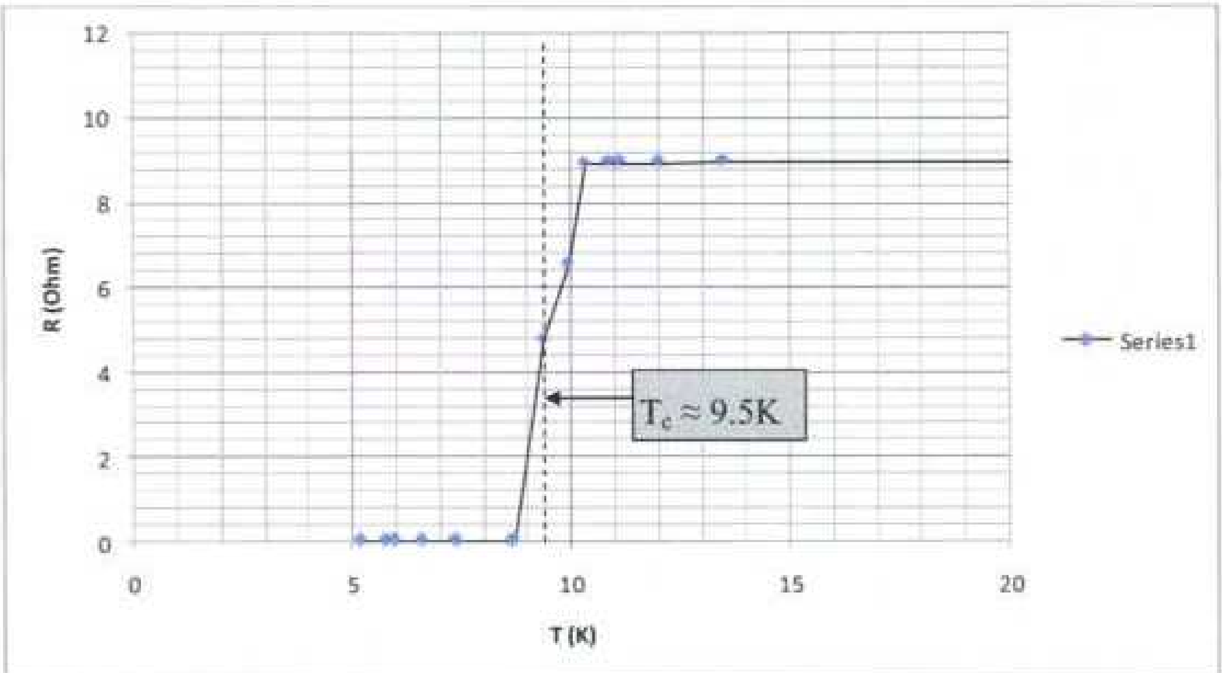
In all the sample achieved a critical temperature of ~9.5K.

Results

With systematic collection of results we found the classic shape of a Resistance-Temperature graph for a superconductor emerging, that of a gradual decline, followed by a sudden drop.



Here we see the transition very clearly, as an almost vertical line down to 0 Ohm resistance over the space of a few degrees, this transition can be seen in more detail here.



Conclusions

My research was by no means 'cutting-edge', however the point of this project was not to break new ground, but rather to give an idea of the more practical work that goes into the running of any scientific lab. Huge particle accelerators are good, but without teams of scientists tending and maintaining them, they'd never work (or even get built).

The work I and my fellow experimenter undertook has provided a working cryocooler, which can be used to test components at extremely low temperatures, which will prove useful for the facility's scientists as they work on projects such as ALICE (Accelerators and Lasers In Combined Experiments) and EMMA (Electron Machine with Many Applications), which hope to utilise accelerator technology to build an energy recovery LINAC (Linear Accelerator), which will allow super efficient accelerators to be built, or accelerators with gigantic energy outputs, as well as use proton beam technology to kill cancerous tumours.

However, over the course of our project, things could have been done better. We found ourselves embattled by large amounts of wiring, which we ended up simplifying because our wiring was not of the highest quality, due to simple inexperience. We also had to overcome various obstacles and problems with insulation and vacuum, as well as a water chiller which did not work properly, but these were unavoidable, and nobody's fault.

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C.R Nave

Acknowledgements

I would like to say a warm thank you to Shrikant Pattalwar and Kai Hock for their invaluable guidance and supervision over the course of setting up an using the cryocooler, as well as providing interesting information about the site, and the physics of superconduction itself.

Personal Statement.

During my time at the Cockcroft institute I have learnt a great deal about the physics of very cold things (cryogenics), as well as gaining a lot of practical experience of science, showing that physics is just as practical as the other two major sciences, maybe more! I certainly did not expect this, but it was a welcome surprise. It has been a varied four weeks, at times menial, but at others interesting, showing me the good and bad points of being a scientist. However I still feel that I benefitted hugely from the placement, and, having seen a superconductor transition first hand, and having been told that many lifelong cryogenic physicists have not, I feel privileged too!